GLACIALLY-TRIGGERED FAULTING

Glacially triggered faulting describes movement of pre-existing faults caused by a combination of tectonic and glacially induced isostatic stresses. The most impressive fault scarps are found in Northern Europe, assumed to have been reactivated at the end of deglaciation. However, this view has been challenged as new faults have been discovered globally with advanced techniques such as LiDAR, and fault activity dating has shown several phases of reactivation thousands of years after deglaciation ended. This book summarizes the current state-of-the-art research in glacially triggered faulting, discussing the theoretical aspects that explain the presence of glacially induced structures and reviews the geological, geophysical, geodetic and geomorphological investigation methods. Written by a team of international experts, it provides the first global overview of confirmed and proposed glacially induced faults and provides an outline for modelling these stresses and features. It is a go-to reference for geoscientists and engineers interested in ice sheet–solid earth interaction.

HOLGER STEFFEN is a geophysicist by training who joined the Geodetic Infrastructure Department at Lantmäteriet, the Swedish Mapping, Cadastral and Land Registration Authority, in 2012 after working for several years as a postdoctoral researcher at universities in Germany, Canada and Sweden. His work deals with glacial isostatic adjustment modelling and corresponding acquisition and/or analysis of geodetic, geophysical and geologic observations. He chairs the Working Group of Geodynamics and Earth Observation of the Nordic Geodetic Commission.

ODLEIV OLESEN is a senior researcher at the Geological Survey of Norway with 40 years of professional experience, including management roles, extensive research and mapping activities. He has taught as Adjunct Professor in Applied Geophysics at the Norwegian University of Science and Technology.

RAIMO SUTINEN is a geo-consultant with 40 years' experience in geoscience. He was previously a senior researcher at the Geological Survey of Finland, where he managed the project 'Postglacial Faults'. He has more than 60 impact and 100 proceedings papers in remote sensing, soil physics and biogeochemistry. His recent research has focused on faults and earthquake-induced landforms.

GLACIALLY-TRIGGERED FAULTING

Edited by

HOLGER STEFFEN
Lantmäteriet

ODLEIV OLESEN
Geological Survey of Norway

RAIMO SUTINEN
Geological Survey of Finland

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning, and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781108490023
DOI: 10.1017/9781108779906

First published 2022

Printed in the United Kingdom by TJ Books Limited, Padstow Cornwall

A catalogue record for this publication is available from the British Library.

ISBN 978-1-108-49002-3 Hardback

Contents

Figures

Tables

Contributors

John Adams
Canadian Hazards Information Service, Natural Resources Canada, Ottawa, Ontario, Canada

Omid Ahmadi
AFRY, Solna, Sweden

Maria Ask
Department of Civil, Environmental and Natural Resources Engineering, Division of Geosciences and Environmental Engineering, Luleå University of Technology, Luleå, Sweden

Tobias Bauer
Department of Civil, Environmental and Natural Resources Engineering, Division of Geosciences and Environmental Engineering, Luleå University of Technology, Luleå, Sweden

Ruth Beckel
Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Albertas Bitinas
Nature Research Centre, Vilnius, Lithuania

Christian Brandes
Institute of Geology, Leibniz University Hannover, Hannover, Germany

Gregory R. Brooks
Geological Survey of Canada, Natural Resources Canada, Ottawa, Ontario, Canada

Åke Fagereng
School of Earth and Ocean Sciences, Cardiff University, Cardiff, United Kingdom

Jeffrey T. Freymueller
Department of Earth and Environmental Sciences, Michigan State University, East Lansing, Michigan, USA

Nicolai Gestermann
Federal Institute for Geosciences and Natural Resources (BGR), Geozentrum Hannover, Hannover, Germany

Steven J. Gibbons
NORSAR, Kjeller, Norway
Norwegian Geotechnical Institute, Oslo, Norway

Sofie Gradmann
Geological Survey of Norway (NGU), Geophysics Section, Trondheim, Norway

Søren Gregersen
Geological Survey of Denmark and Greenland, København K, Denmark

Susanne Grigull
Swedish Nuclear Fuel and Waste Management Company (SKB) Solna, Sweden, Sweden
Geological Survey of Sweden, Uppsala, Sweden

Fredrik Høgaas
Geological Survey of Norway (NGU), Quaternary Geology Section, Trondheim, Norway

Eija Hyvönen
Geological Survey of Finland, Rovaniemi, Finland

Tor Arne Johansen
Department of Earth Science, University of Bergen, Bergen, Norway

Christopher Juhlin
Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Marie Keiding
Department of Geophysics, Geological Survey of Denmark and Greenland, København K, Denmark

Annakaisa Korja
Department of Geosciences and Geography, Institute of Seismology, University of Helsinki, Helsinki, Finland

Ilmo Kukkonen
Department of Geosciences and Geography, University of Helsinki, Helsinki, Finland

Tormod Kværna
NORSAR, Kjeller, Norway

Jurga Lazauskienė
Department of Geology and Mineralogy, Institute of Geosciences, Vilnius University, Vilnius, Lithuania

Thomas Lege
Federal Institute for Geosciences and Natural Resources (BGR), Geozentrum Hannover, Hannover, Germany

Conrad Lindholm
SeismoConsult, Vittenbergvn, Fjellhamar, Norway

A. J. (Tom) van Loon
College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao, China

Henning Lorenz
Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Björn Lund
Swedish National Seismic Network, Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Alireza Malehmir
Department of Earth Sciences, Uppsala University, Uppsala, Sweden

Mira Markovaara-Koivisto
Geological Survey of Finland, Espoo, Finland

Jussi Mattila
Rock Mechanics Consulting Finland Oy, Vantaa, Finland

Maarit Middleton
Geological Survey of Finland, Rovaniemi, Finland

Henrik Mikko
Geological Survey of Sweden, Uppsala, Sweden

Katharina Müller
Institute of Geology, Leibniz University Hannover, Hannover, Germany

Raymond Munier
Terra Mobile Consultants AB, Stockholm, Sweden

Svetlana B. Nikolaeva
Geological Institute, Kola Science Center, Russian Academy of Sciences, Apatity, Murmansk region, Russia

Andrey A. Nikonov
Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

Kati Oinonen
Department of Geosciences and Geography, Institute of Seismology, University of Helsinki, Helsinki, Finland

Antti E. K. Ojala
Geological Survey of Finland, Espoo, Finland
Department of Geography and Geology, University of Turku, Finland

Odleiv Olesen
Geological Survey of Norway (NGU), Geophysics Section, Trondheim, Norway

Lars Olsen
Geological Survey of Norway (NGU), Quaternary Geology Section, Trondheim, Norway

Jukka-Pekka Palmu
Geological Survey of Finland, Espoo, Finland

Małgorzata (Gosia) Pisarska-Jamroży
Institute of Geology, Adam Mickiewicz University, Poland

Thomas Plenefisch
Federal Institute for Geosciences and Natural Resources (BGR), Geozentrum Hannover, Hannover, Germany

Chris Rollins
School of Earth and Environment, University of Leeds, Leeds, United Kingdom

Jan-Erik Rosberg
Engineering Geology LTH, Lund University, Lund, Sweden

Natalia A. Ruppert
Alaska Earthquake Information Center, Geophysical Institute, University of Alaska, Fairbanks, Alaska, USA

Timo Ruskeeniemi
Geological Survey of Finland, Espoo, Finland

Jonny Rutqvist
Energy Geosciences Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Bent Ole Ruud
Department of Earth Science, University of Bergen, Bergen, Norway

Peter B. E. Sandersen
Geological Survey of Denmark and Greenland, Department of Groundwater and Quaternary Geology Mapping, Århus C, Denmark

Jeanne Sauber
Geodesy and Geophysics Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Sergey V. Shvarev
Institute of Geography, Russian Academy of Sciences, Moscow, Russia
Schmidt Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia

Colby A. Smith
Geological Survey of Sweden, Uppsala, Sweden

Thomas Spies
Federal Institute for Geosciences and Natural Resources (BGR), Geozentrum Hannover, Hannover, Germany

Holger Steffen
Lantmäteriet, Geodetic Infrastructure, Gävle, Sweden

Rebekka Steffen
Lantmäteriet, Geodetic Infrastructure, Gävle, Sweden

Raimo Sutinen
Geological Survey of Finland, Rovaniemi, Finland

David C. Tanner
Leibniz Institute for Applied Geophysics (LIAG), Hannover, Germany

Marja Uski
Department of Geosciences and Geography, Institute of Seismology, University of Helsinki, Helsinki, Finland

Peter H. Voss
Geological Survey of Denmark and Greenland, København K, Denmark

Jutta Winsemann
Institute of Geology, Leibniz University Hannover, Hannover, Germany

Piotr Paweł Woźniak
Department of Geomorphology and Quaternary Geology, University of Gdańsk, Gdańsk, Poland

Patrick Wu
Department of Geoscience, University of Calgary, Calgary, Canada

Preface

On cloudless summer days in Northern Europe one may spot a small plane crossing the sky like a farmer tilling a field. This plane may be collecting data for a digital elevation model using laser scanning.

During analysis of novel digital elevation data in the early 2010s, a peculiar feature in the form of an almost north–south-oriented lineation was found near the town of Bollnäs in Sweden, approximately 250 km north of Stockholm. After additional investigation on the ground, a glacially induced fault was identified. This was surprising, since the location is more than 400 km south of the area with the prominent scarps of all the glacially induced faults known at that time.

As more faults were identified later in Sweden and Finland with this type of new data, a series of Postglacial Fault Symposia (2015 in Uppsala, Sweden; 2016 in Turku, Finland; 2018 in Kautokeino, Norway) were organized to provide a fruitful forum for the exchange of the newest research results.

In addition, the Postglacial Fault Drilling Project was initiated in 2010 through a workshop in Skokloster, Sweden, funded by the International Continental Scientific Drilling Program. It was recognized that a glacially induced fault represents a special kind of intraplate fault zone. The full drilling proposal, 'Drilling Active Faults in Northern Europe' (DAFNE), was approved in October 2019.

In 2016, in view of the many new results and the planned drilling, the participants of the Postglacial Fault Symposium decided to summarize the findings of the last 50 years up to the present day in a book to be entitled *Glacially-Triggered Faulting*. Two editors were proposed: Robert Lagerbäck and Odleiv Olesen.

Sadly, Robert Lagerbäck had to decline his editorship and passed away in August 2018. Robert Lagerbäck was employed at the Geological Survey of Sweden (SGU) and was the key researcher on the so-called postglacial faults in northern Fennoscandia for more than three decades. In the 1980s, Robert was one of the key persons to map these faults within the Nordkalott Project. With his death,

we lost a renowned geologist, whose expertise was often missed during this book's preparation. We hope he would have liked the final product.

We would like to thank all authors and reviewers of the book and the chapters, and we thank the contributors to the *International Database of Glacially Induced Faults*, by Munier et al. (2020), which is available for download at the *PANGAEA* website, doi.org/10.1594/PANGAEA.922705.

This book could not have been edited without them. In addition, we are very grateful for the excellent assistance by Susan Francis and Sarah Lambert from Cambridge University Press during the preparation of this book.

We hope the reader will find this book the ideal reference in the field of glacially triggered faulting. It should also serve as the best comprehensive start for a new generation of scientists working on glacially induced faults.

And finally, during the writing of this book, the authors welcomed at least five new arrivals. Perhaps they will form the next generation of researchers investigating glacially induced faults. There is still much to do. Data collection and research will continue; there will be many more cloudless days in Northern Europe and elsewhere. The next time you see a small plane crossing the sky like a farmer tilling a field, imagine that it may be collecting the data that will help unravel another secret of glacially triggered faulting.

Robert Lagerbäck leading his 2012 fault excursion at the Lansjärv site, northern Sweden (Photo: Raimo Sutinen).